University of New Brunswick Fire Science Centre

Evaluation of "Tank Car Thermal Modeling Phase I"

by H.G. Engineering

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J.E.S. Venart, P.Eng.

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17. Abstract

The report documents the evaluation of "Tank Car Thermal Modelling" (by H.G. Engineering, TP 3988E, 31 August 1982), which develops mathematical model of heat transfer processes in an LPG carrying rail tank car exposed to a fire environment. The proposed model is intended for use in the analysis of the results of experimental tests of a tank car protective system and in the development of alternative designs of the protective system.

The evaluation was carried out by critically reviewing and assessing the reported work in terms of the problem physics, assumptions, initial and boundary conditions, mathematical formulation and proposed numerical methods. The feasibility of the approach proposed for the remaining phases and the completeness of the report are also analysed and assessed in detail.

It is concluded that the physics of several important aspects of the phenomena have been identified and analysed. The numerical models proposed for a solution, however, require considerable more detail before a definitive evaluation of the proposed approaches is possible.

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17. Résumé

Ce rapport évalue l'étude intitulée "Tank Car Thermal Modelling" (par H.G. Engineer, TP 3988E, août 1982) qui proposait un modèle mathématique des flux thermiques à l'intérieur d'un wagon-citerne transportant du gaz de pétrole liquifié et pris dans une conflagration. Cette modélisation doit servir à l'analyse des résultats des essais d'un système nouveau de protection des wagons-citernes et aussi à la mise au point de configurations nouvelles dudit système.

L'évaluation se fonde sur une analyse critique des points suivants: caractérisation physique du problème, hypothèses de départ, conditions initiales et aux limites, formulation mathématique et méthode de résolution numérique. Elle porte également sur la faisabilité des phases à venir de l'étude, en plus de considérer dans quelle mesure cette dernière fait le tour de la question.

Le rapport conclut que plusieurs phénomènes physiques importants qui caractérisent le problème ont été cernés et analysés. Par contre, la méthode numérique proposée pour la résolution des équations de la modélisation n'est pas développée de façon suffisamment détaillée pour permettre une évaluation définitive de la voie proposée pour l'étude de ce problème.

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Summary

Under the terms of agreement for the service contract No. 4710 dated 22nd of March 1982, the University of New Brunswick Fire Science Centre has carried out the evaluation of the draft report entitled "Tank Car Thermal Modeling" dated August 31, 1982 by H.G. Engineering and Hooper Angus Ltd.

This project was performed as part of the Tank Car Explosion Protection Program - Phase I, which has the primary objective of developing a mathematical model of heat transfer made in a rail tank car under fire conditions. H.G. Engineering and Hooper and Angus Associates Ltd. have reviewed the data of 1/5 scale and full scale tests reported by Canadian and U.S. investigators. Their explanations of the observed sequence of events, specifically as they relate to the results of TP2740(*), appear to be substantially correct.

The consideration of the tank exterior boundary conditions, due to the pool and valve flame, and the tank interior fluid (propane liquid and vapour) boundary conditions do not appear to be researched in sufficient depth to provide their proposed numerical model with any function other than a fitting procedure. In particular, the magnitude of the variation in heat transfer coefficients inside and outside the tank, the uncertainty in fluid level, and the proposed "interface" exchange resistances are expected to be highly dependent upon scale and hence provide uncertainty in future full scale design studies with EXPLOSAFE.

The model appears to be unduly complex for the existing experimental data base. Simple models, wherein all the boundary conditions can be specified should be considered before the complexity is increased. Further, the proposed experimental work should be more precisely defined and justified.

(*) "Testing and Evaluation of the EXPLOSAFE system, as a method of controlling the Boiling Liquid Expanding Volume Explosion (BLEVE)" TP2740, R.D. Appleyard, Dept. of Res. & Dev. EXPLOSAFE Div. of Vulcan Ind. Packaging Ltd., August 1980.

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1. Introduction

This document reports the preliminary evaluation of the draft report entitled "Tank Car Thermal Modeling" dated August 31, 1982 by H.G. Engineering and Hooper and Angus Ltd.

The objectives of the evaluation are to:

i) Study the report in order to become familiar with the approach taken by the contractors and

ii) evaluate the report with respect to problem physics, assumptions, initial and boundary conditions, mathematical formulation, proposed numerical methods, proposed approach for the remaining phases, and completeness.

The evaluation was prepared by Dr's. J.G. Lenard, A.C.M. Sousa, F.R. Steward and J.E.S. Venart under the terms of the Transportation Development (TDC) Service Contract No. 4710 dated March 22, 1982.

In the following we describe in detail our evaluation of the Contractor's report under the items listed above.

2. Problem Physics and Assumptions

The contractor's explanation of the observed sequence of events (Section 2.2) appears to be substantially correct. They have identified that in addition to the exterior condition of the engulfing pool or torch fire the presence of the pressure reliev valve (PRV) flare may influence heat transfer in the upper regions of the tank. They have further identified that "thermal softening" of the PRV spring may play a major role in the long time pressure response of the tank and contents, especially those protected with EXPLOSAFE.

The importance of vapour compression and superheating due to liquid expansion prior to and during initial valve opening is stated to be very significant in the 1/5 scale tests. Its effects are overstated for the full scale tests examined [13].

The "boiling and flashing" of the liquid, the role of liquid "overpressure" and the presence of significant thermal stratification, justify their selection of a two zone liquid model.

The strong vapour temperature gradients in the 1/5 scale tests, both with and without EXPLOSAFE, appear to permit the inclusion of both the radiative and convective components proposed for their model.

The proposed inference of liquid level from wall temperature departures from saturation is however doubtful. All past methods, both experimental and numerical, have attempted similar techniques and results do not always agree with the estimated time dependent liquid inventory [13,14]. In any model it is imperative that the time varying liquid/vapour inventory be known. The transient two phase swelling due to homogeneous nucleation of the liquid must also be considered and may possibly be evaluated using techniques similar to those proposed in Reference [12].

The simple boiling experiments employing EXPLOSAFE are interesting as well as the qualitative explanation of its role in the 1/5 scale tests. The lack of quantitative results and comparison is however disappointing.

Pressure relief valve functioning and proposed modeling is, as was noted previously, adequate. No quantitative model is however proposed for valve spring softening and for initial valve mass flows. The latter, from full scale tests, are known to depart substantially from single phase choked flow and hence affect the apparent liquid level substantially; for example, [13] reports initial valve coefficients of ~ 0.4 versus the 0.88 recommended by Sallet [15].

3. Initial and Boundary Conditions

The boundary conditions to the model proposed by the contractors for both pool and torch fire conditions are described in very general and qualitative terms only. From their description of the pool fire model (Sect. 5.6) it is apparent that many of the thermal resistances proposed may only be obtained by a "fit" of existing experimental evidence. It is

apparent that such a model could be particularly sensitive to the values "chosen" for the interface resistances between liquid, subcooled core, and vapour. Significant scale effects must hence be anticipated. A more detailed and quantitative evaluation of the boundary conditions would have been desirable.

4. Mathematical Formulation and Proposed Numerical Methods

The model formulation, its programme logic and its various subroutines have been treated extensively in sections 5 and 6 of the report. The model chosen is a two region liquid, one region vapour, representation of the unsteady state energy equation - closed system representation with closed PRV and open system representation with PRV open. The propane properties required are derived from tabular representations previously stored. The simulation logic for the pool and impinging torch models appears comprehensive and complete.

The location of phase and zone boundaries has been considered for the horizontal tank only. The external fire condition is modeled as radiation only. References [2] and [9] have shown there can be significant convective heating. The ratio of convected to total heat transfer was found to be variable around the diameter of a cylinder immersed in a JP4 fire [9], values varied between 0.173 to 0.628 for an 8.530 inch diameter cylinder thus raising the question as to the suitability of only including radiation.

The determination that the PRV flare may play a significant role in the ullage space heat transfer is important. The estimate of the radiation load from the PRV flare is however relatively simple. The flare is not spherical and adds significantly to the thermal load on the tank depending upon configuration and wind. References [1] and [3] may be utilized to determine that this source of heating may be between 11 and 18 kW/m^2 near the base of the flare.

The fluid properties subroutine (Section 6:3.7), state equations for the liquid and vapour (Sect. 6:3.16-17), and

vapour pressure (6:3.20), utilize digitized values of tables. Explicit representation may be obtained more efficiently with programmes obtained from reference [11].

Explosafe representation requires effective conductivities and specific heats in addition to density, surface area, and void fraction. The effective thermal conductivity of the liquid - EXPLOSAFE matrix is infinite under boiling conditions [10]. Its behaviour may be estimated using reference [6]; critical or dryout heat fluxes estimated in this matter suggest values in excess of 5 Mw/m^2, a value which greatly exceeds the critical heat flux reported for propane. The vapour - EXPLOSAFE matrix properties may be estimated utilizing their proposed methods.

The evaluation of the mixing coefficients R_m are to be determined by numerical experiment. It was pointed out previously that accurate assessment of these parameters is essential for success of the proposed model. It was further noted that this parameter would most likely be very scale dependent [16].

In considering the proposed process equations the stage I equations (PRV closed) are governed by the rate of increase of internal energy to the liquid and vapour and the fact that the process is one of constant specific volume. In stage II (PRV open) some more justification is certainly necessary for the inclusion of the condition of constant vapour specific volume over all the period the PRV is open, the data [10] will equally support, for all but the largest times, a constant pressure condition.

The PRV set point subroutine (6:3.24) is essentially a "fit" to experimental data and does not model the mechanism of heat transfer to the valve spring and its subsequent time-temperature-strength behaviour. The procedure proposed will certainly model the behaviour for the 1/5 scale tests, however it will be of little use for full scale design.

The subroutines (Sections 6:3.2) determining liquid level are satisfactory for conditions where there is no homogeneous boiling of the bulk liquid in the stratified heated liquid layer. Boiling in this region will greatly influence the presumed interface and hence the heat transfer. The boundary conditions, both on the presumed surface and at the walls will likewise be affected due to the two-phase nature of this region.

Structural considerations and the failure criteria have been examined in Sections 6:3.23 and 7.0. It is concluded that the primary cause of failure is due to a combination of pressure and severely reduced material strength. The maximum steel temperature and a digitized steel strength temperature representation are to be compared to the stress due to the interval pressure at the current time step. If the actual stress exceeds that permissible failure will be considered to have occurred. It must be considered that such a model is only the first step towards a definitive statement of failure.

Little detail is given to the proposed solution of the heat transfer and thermodynamic equations and hence estimates of computer requirements cannot be made.

5. Proposed Approach for Remaining Phases

Their proposed models for torch and pool fires are distinct. There is every possibility that a combined pool/torch condition will be the most severe case. There will be difficulties in attempting this with their models. The supporting information considered necessary for the remaining phases is discussed in Sections 8 and 9. This includes:

i) Boiling curves for propane
ii) EXPLOSAFE effects on heat transfer
iii) Thermodynamic properties of propane
iv) Heat transfer coefficients and properties
v) Mechanical Properties and Tank Materials
vi) Further data on EXPLOSAFE
vii) Vent valve characteristics.

6. Completeness

The report is incomplete in that although a description of the detailed physics of the phenomena has been stated and a theoretical and numerical model proposed, the specific implementation details are at this stage somewhat vague, untested and/or undemonstrated. The condition of a horizontal tank only has been considered. The plan for supporting analysis and experimental work has not been clearly outlined.

7. Conclusion

The report entitled "Tank Car Thermal Modeling" by H.G. Engineering Ltd. has been reviewed and examined. It is concluded that the physics of several important aspects of the phenomena have been identified and analysed. The numerical models proposed for a solution however require considerable more detail prior to one being able to make a definitive evaluation as to the potential success of the proposed approaches.

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